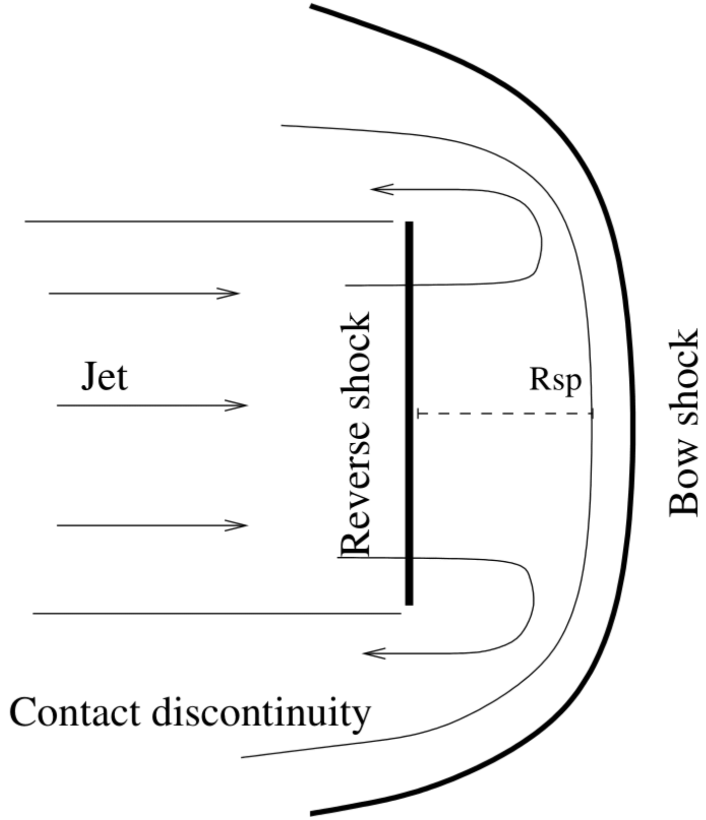
Collision between radiative and adiabatic supersonic flows

Quentin MORENO-GELOS

Anabella ARAUDO Antoine GINTRAND
Vladimir TIKHONCHUK Stefan WEBER

Adiabatic and radiative shocks in protostellar jets

The termination shocks in protostellar jets



High densities: radiative shocks are expected to form.

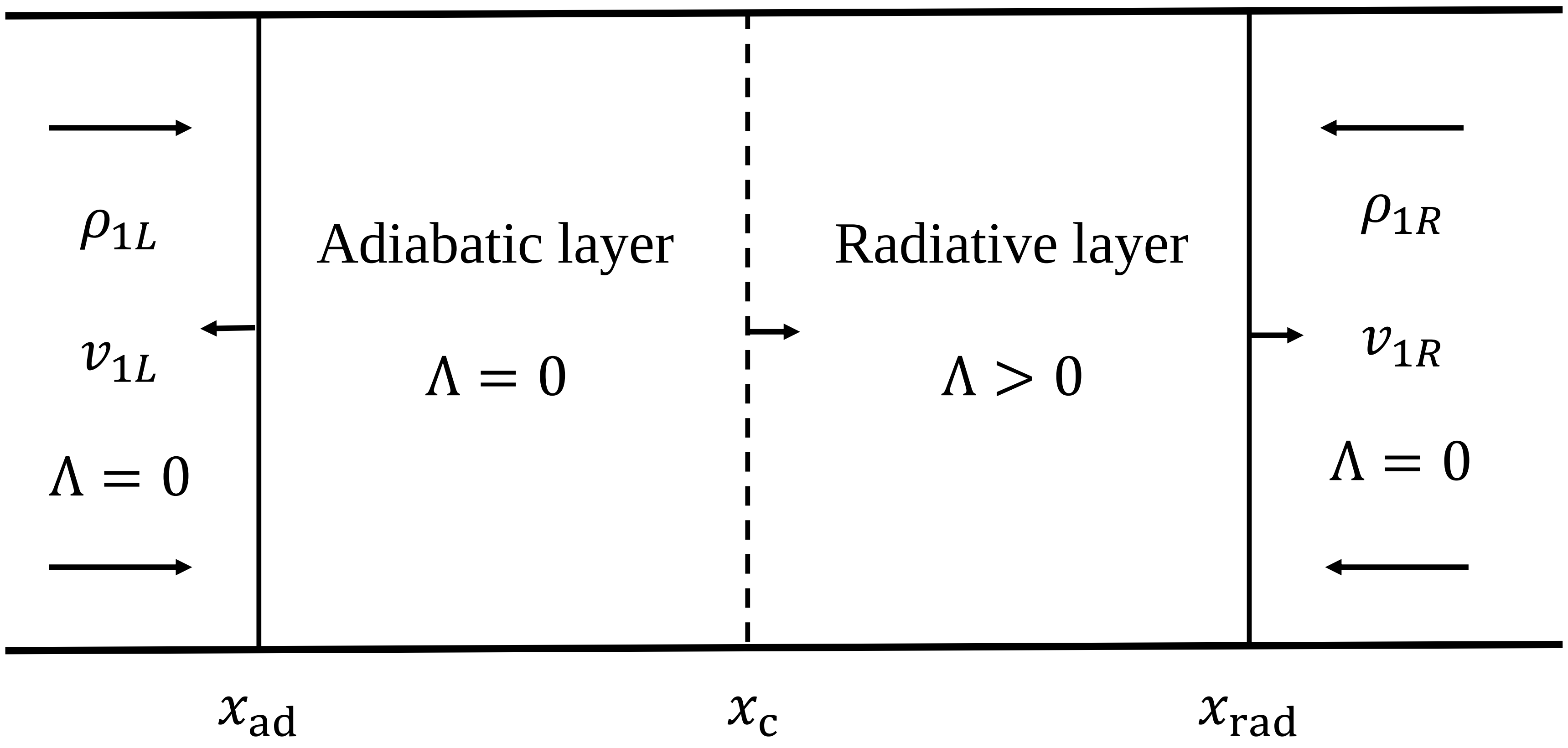
High velocities: adiabatic shocks is also possible.

Adiabatic shocks: efficient at particle acceleration

Radiative shocks: strongly compress the gas.

} γ-ray emission by inelastic p-p collisions

Sketch of the interaction between two constant supersonic flows



General equation of the model

$$\partial_t \rho + \partial_x (\rho\, v) = 0$$

$$\partial_t v + v \partial_x v + \frac{1}{\rho} \partial_x P = 0$$

$$\partial_t \left(\frac{1}{2} \rho\, v^2 + \; e \right) + \partial_x \left[v \left(\frac{1}{2} \rho\, v^2 \; + \; e + P \right) \right] = -\Lambda$$

Cooling time/lenght

$$t_{\mathrm{cool}} = \frac{P_{2R}(0)}{(\gamma_R - 1)\Lambda_{2R}(0)}$$

$$x_{\mathrm{cool}} = V_{1R}(0) t_{\mathrm{cool}}$$

Perfect gas

$$(\gamma - 1) e = P = \rho\, k\, T / m$$

Adiabatic shock jump conditions

$$\frac{\rho_2}{\rho_1} = -\frac{V_1}{V_2} = \frac{\gamma + 1}{\gamma - 1}, \qquad \frac{P_2}{\rho_1 V_1^2} = \frac{2}{\gamma + 1}$$

$$V_{1L,R} = \left| S_{L,R} - v_{1L,R} \right|$$

$$V_{2L,R} = \left| S_{L,R} - v_{2L,R} \right|$$

Self-similar analysis

$$\rho = \rho_{1R} n(\xi), \qquad v = V_{1R} u(\xi) + S_R \xi, \qquad \frac{kT}{m} = V_{1R}^2 z(\xi), \qquad \xi = \frac{x}{x_{\mathrm{ra}}}$$

$\Lambda = \frac{C_R}{t}$ is self-similar and homogeneous inside the layer

$$\frac{dn}{d\xi} = \frac{\alpha\lambda(\gamma_R - 1)}{u(\gamma_R z - u^2)}$$

$$\frac{du}{d\xi} = \frac{\alpha[\lambda(\gamma_R - 1) + \gamma_R n z - n u^2]}{n(\gamma_R z - u^2)}$$

$$\frac{dz}{d\xi} = \frac{\alpha\lambda(\gamma_R - 1)(u^2 - z)}{n u(\gamma_R z - u^2)}$$

Normalized parameters

$$\alpha = \frac{S_R}{V_{1R}}$$

$$\lambda = \frac{C_R}{\rho_{1R} V_{1R}^2} \propto \frac{t}{t_{\mathrm{cool}}}$$

Self-similar profile of the shell

$\eta = 0$ discontinuity

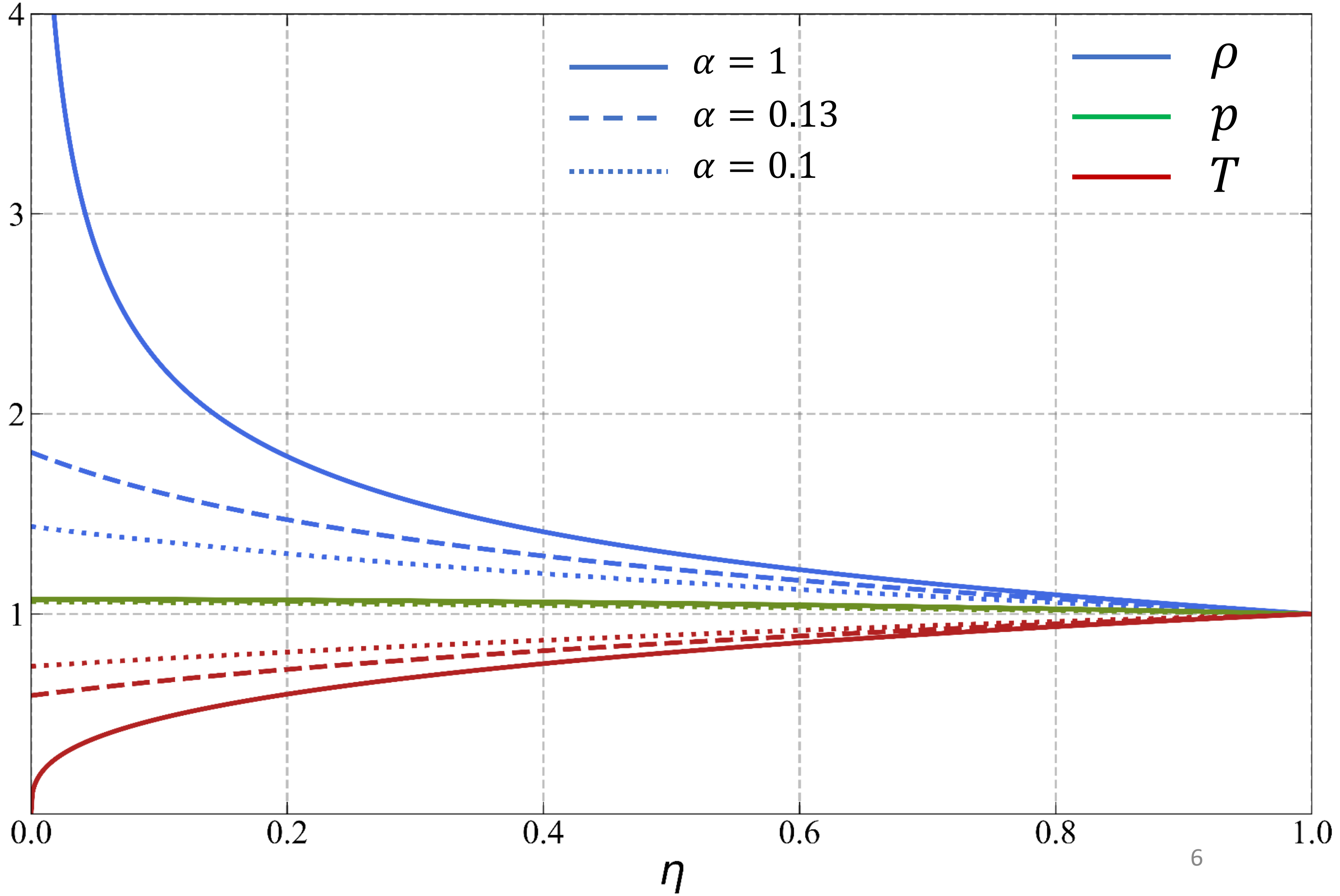
$\eta = 1$ shock front

Adiabatic shock jump conditions

$$\frac{\rho_{II}}{\rho_I} = \frac{\gamma + 1}{\gamma - 1},$$

$$\frac{V_{II}}{V_I} = \frac{\gamma - 1}{\gamma + 1},$$

$$T_{II} = \frac{2(\gamma_R - 1)}{(\gamma_R + 1)^2} V_I^2$$



Parameter space

BRP-solutions

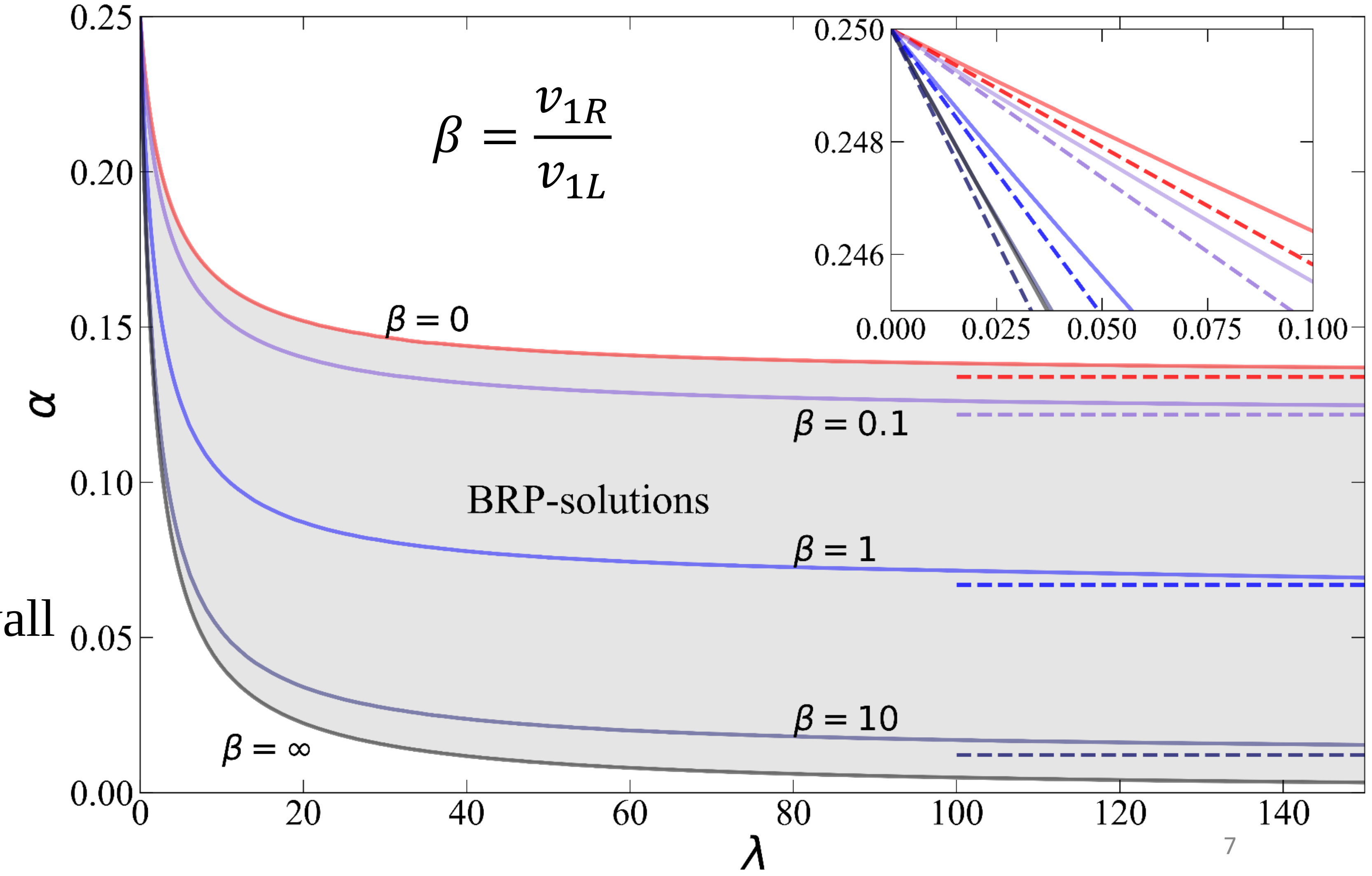
$$\rho_{1L} v_{1L}^2 = \rho_{1R} v_{1R}^2$$

$$\beta = 0$$

infinitely light adiabatic gas

$$\beta = \infty$$

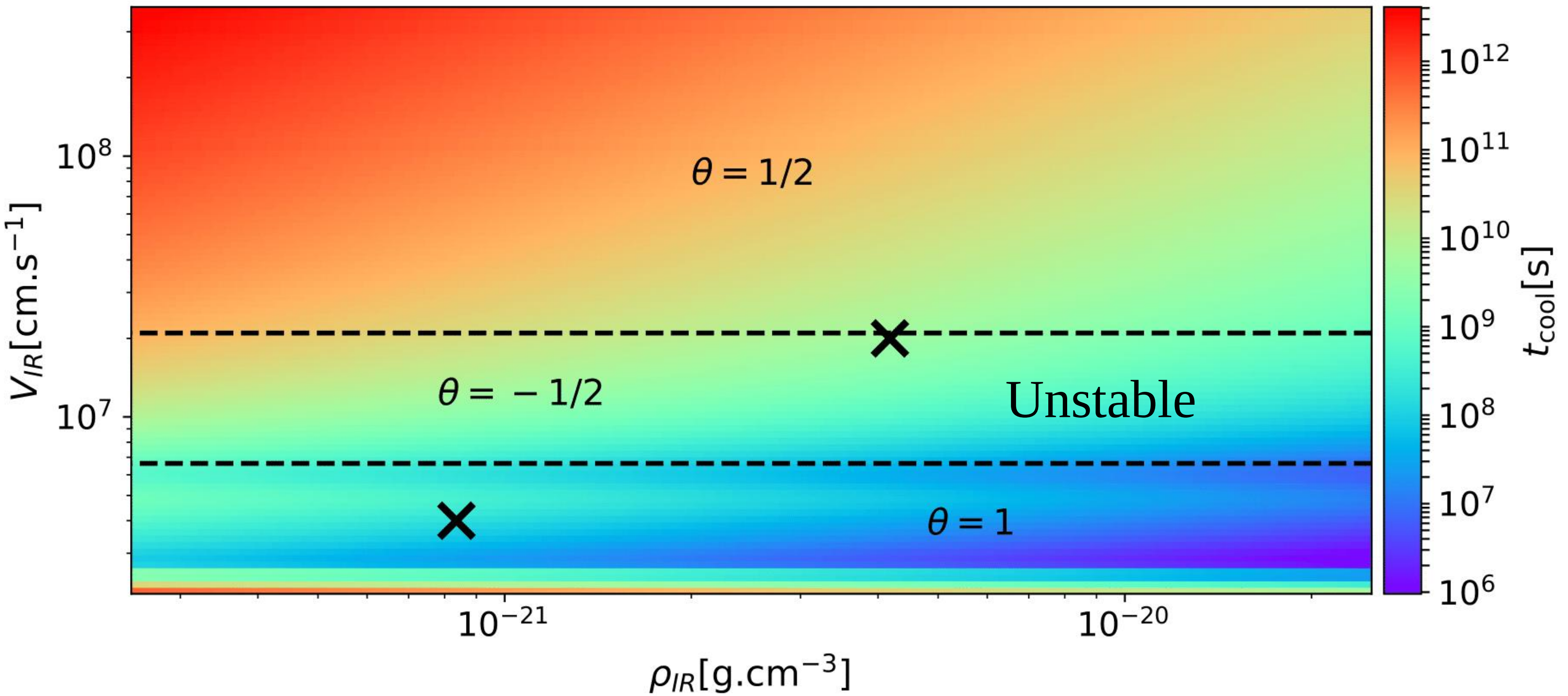
radiative flow reflected from a wall



ASTROPHYSICS / LABORATORY EXPERIMENTS

Sutherland & Dopita (1993)

$$\Lambda \propto \rho^2 T^\theta$$

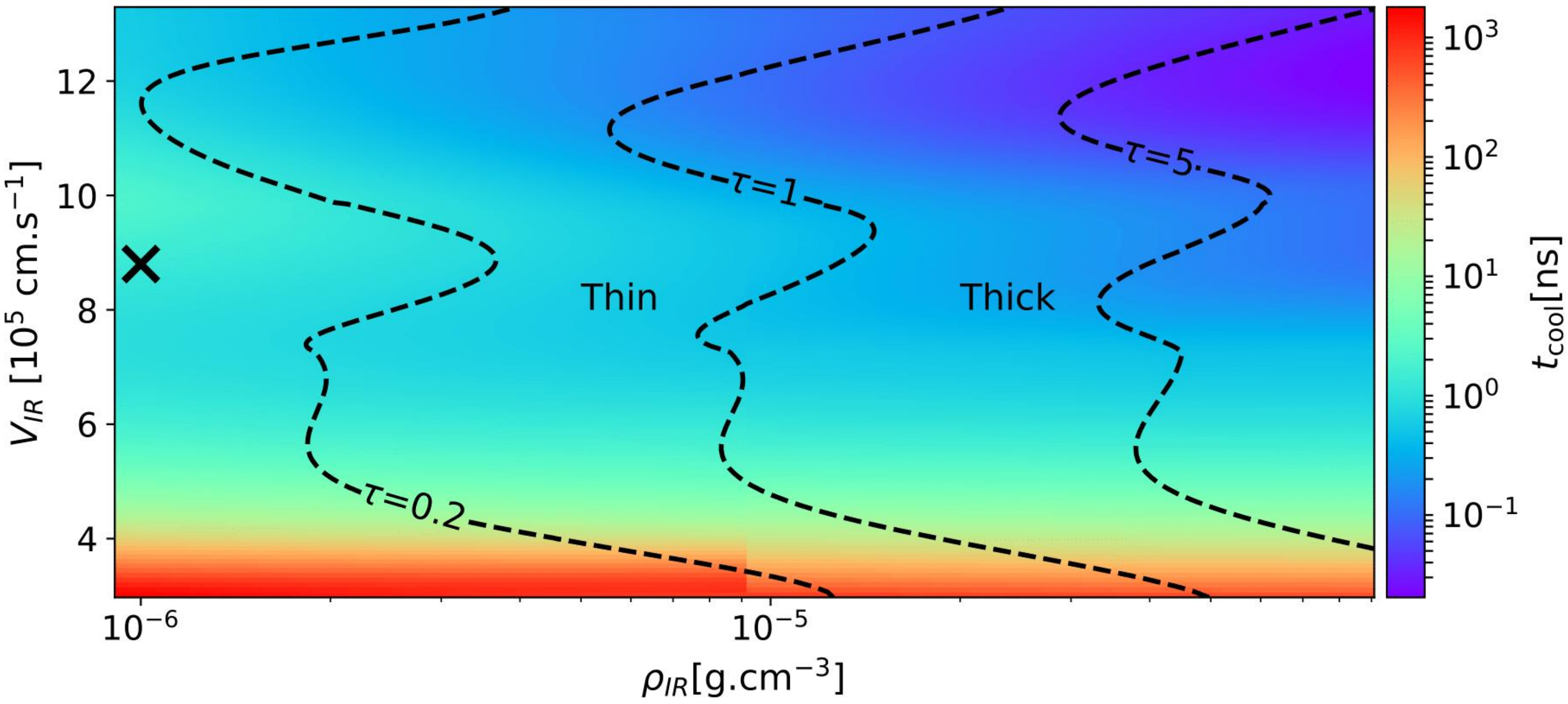


ASTROPHYSICS / LABORATORY EXPERIMENTS

Rodriguez et al. (2012)

Optical depth

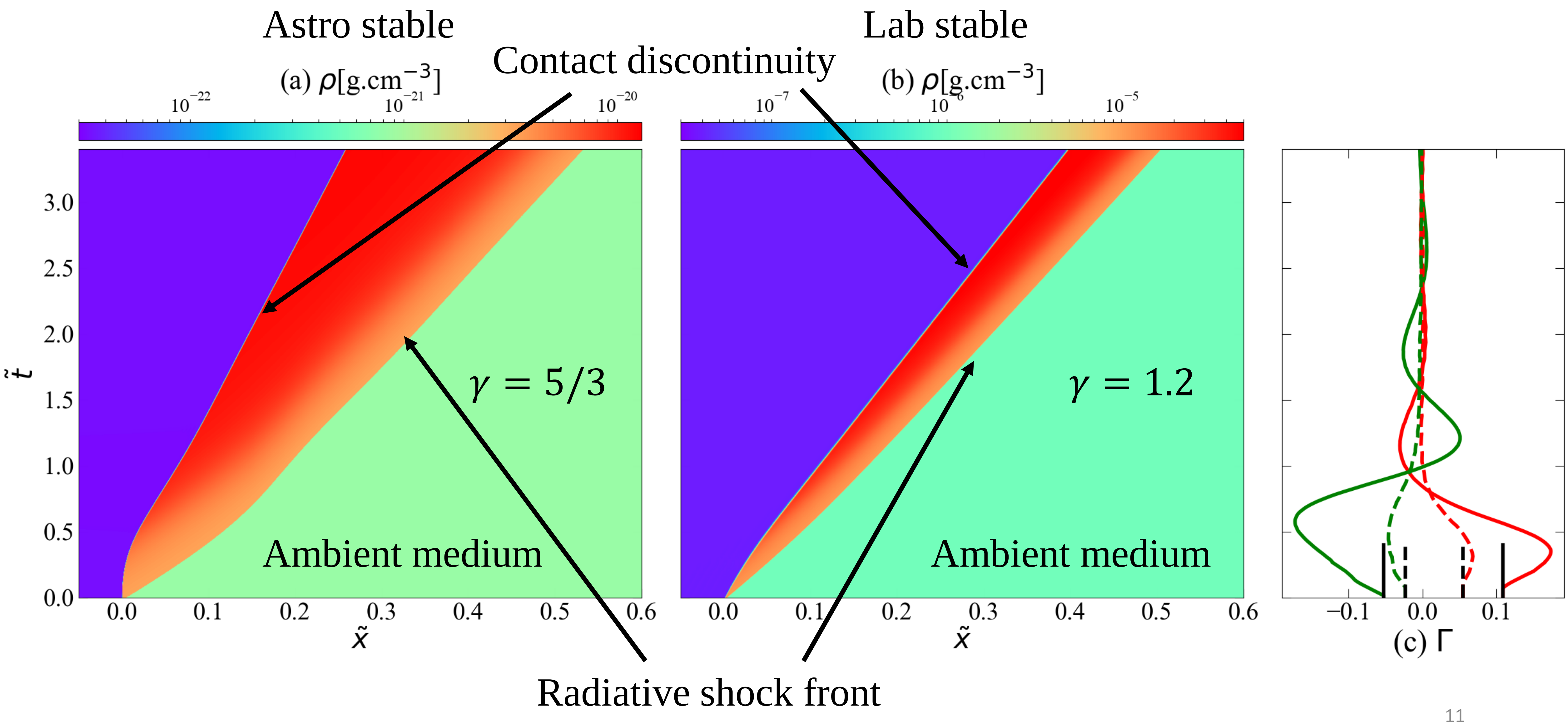
$$\tau = \kappa L$$



ASTROPHYSICS / LABORATORY EXPERIMENTS

Plasma	Astro stable		Astro unstable		Lab	
	Left	Right	Left	Right	Left	Right
γ	$5/3$	$5/3$	$5/3$	$5/3$	$5/3$	1.2
μ_i	1	1	1	1	1	131
ρ_1 [g.cm^{-3}]	8.36×10^{-24}	8.36×10^{-22}	4.18×10^{-23}	4.18×10^{-21}	10^{-8}	10^{-6}
v_1 [cm.s^{-1}]	3×10^{7}	-3×10^{6}	1.5×10^{8}	-1.5×10^{7}	8×10^{6}	-8×10^{5}
T_1 [K]	10^{3}	10^{2}	10^{3}	10^{2}	10^{3}	10^{3}
t_{cool} [s]	-	8.19×10^{7}	-	4.78×10^{9}	-	1.33×10^{-9}
x_{cool} [cm]	-	3.27×10^{14}	-	9.55×10^{16}	-	1.42×10^{-3}
$[x_{\mathrm{min}}, x_{\mathrm{max}}]$ [cm]	$[-3 \times 10^{15}, 10^{15}]$		$[-1.2 \times 10^{18}, 1.2 \times 10^{17}]$		$[-3 \times 10^{-2}, 3 \times 10^{-3}]$	
t_{max} [s]	4×10^{8}		2×10^{10}		6×10^{-9}	

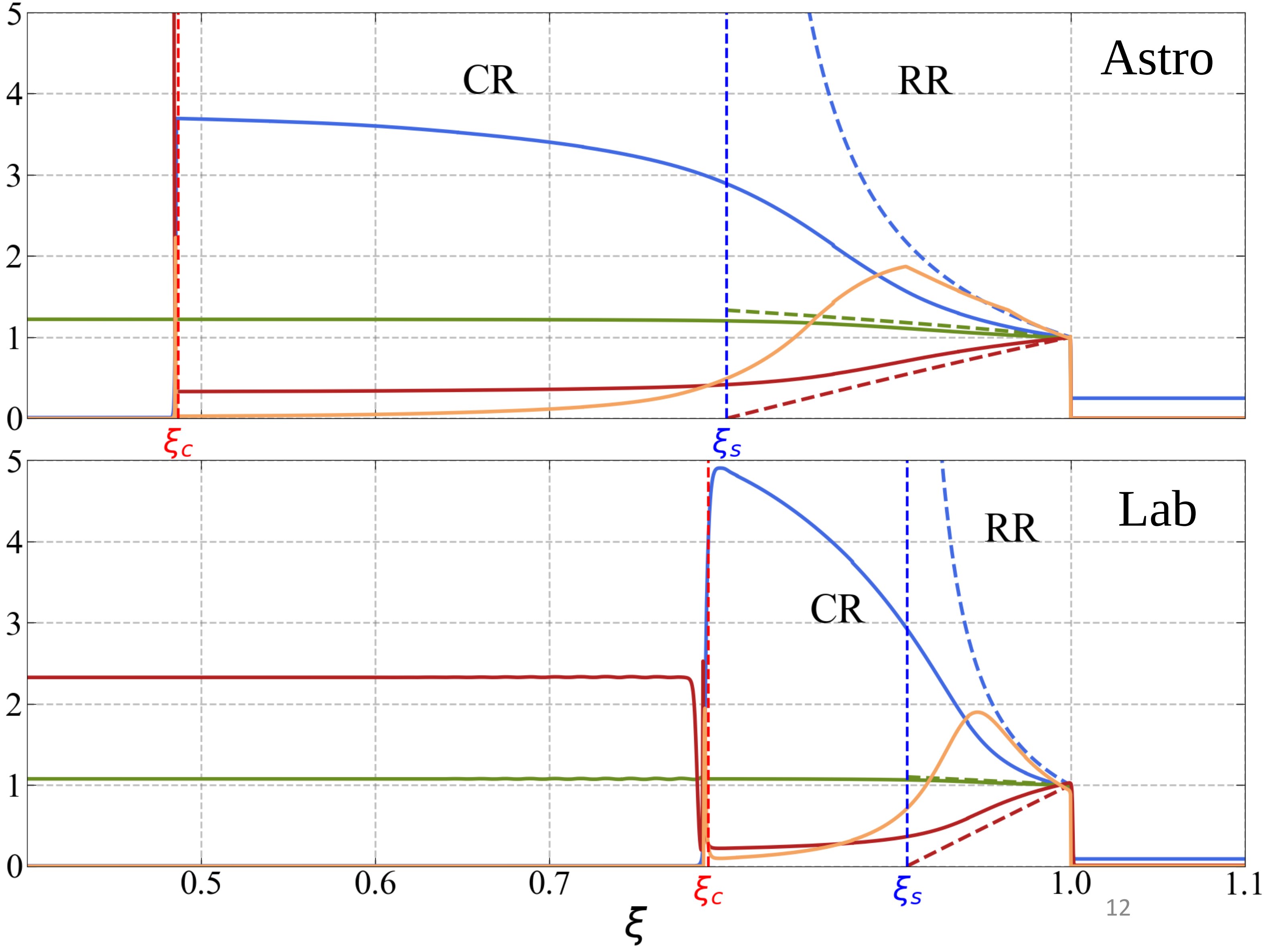
Thermally stable solutions



Thermally stable solutions

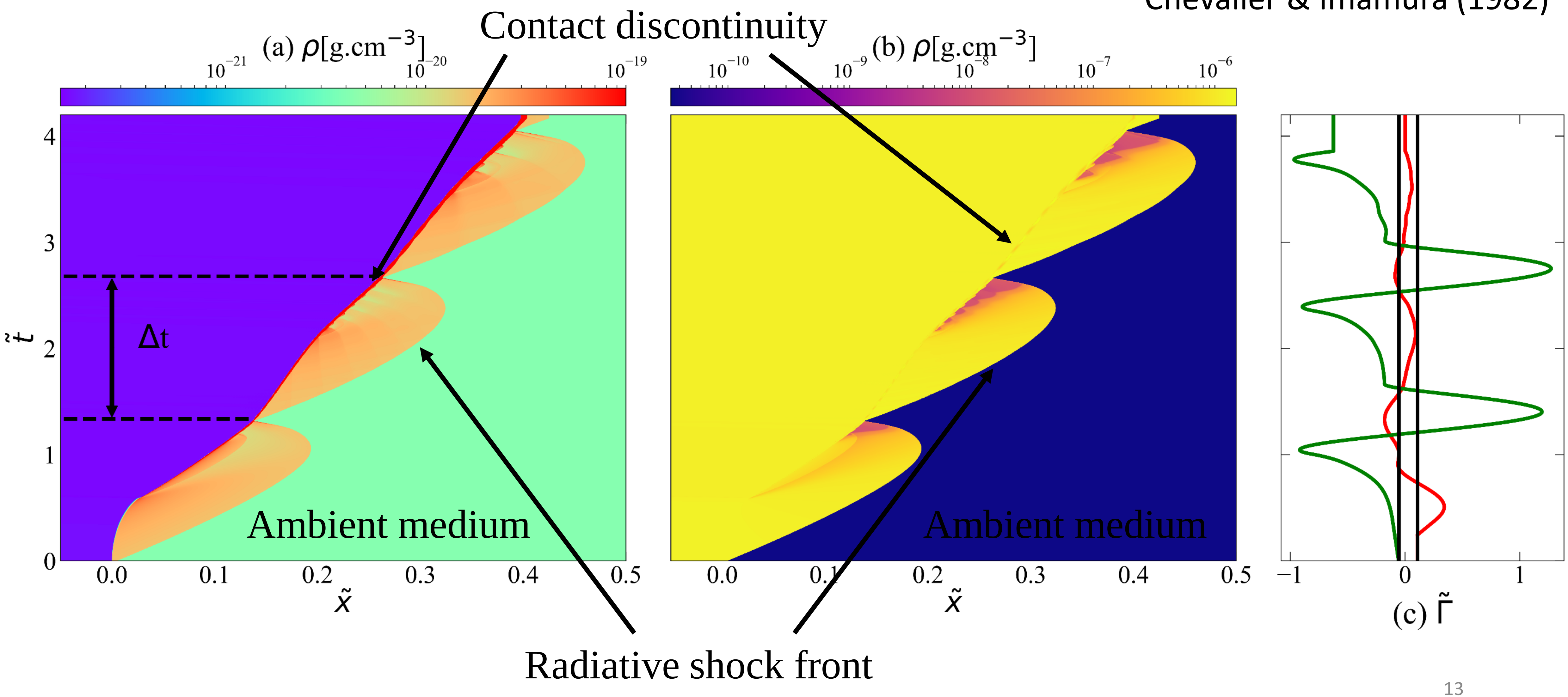
Cooled Region (CR)

Radiative Region (RR)

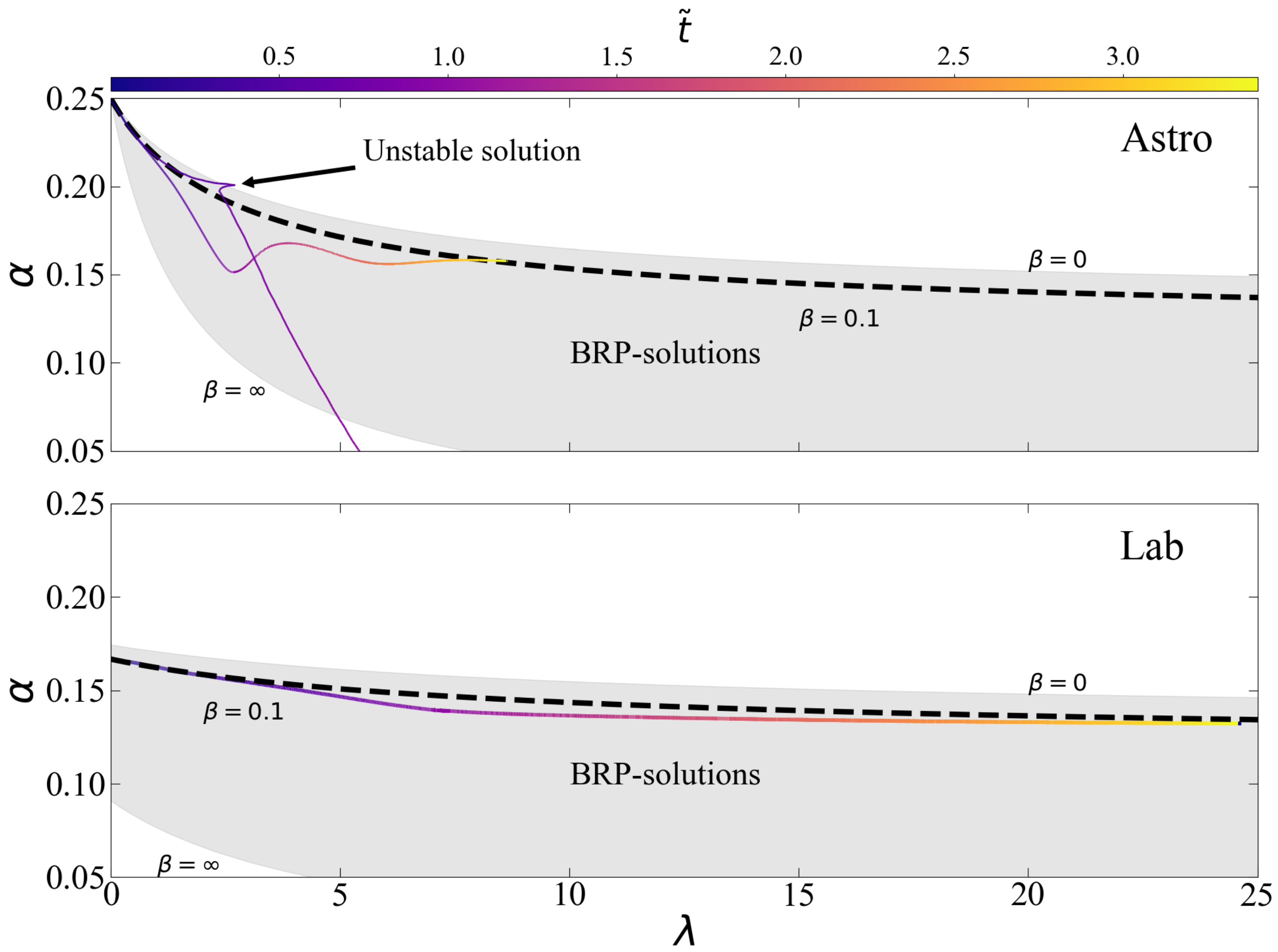


Thermally unstable solutions

Chevalier & Imamura (1982)



Parameter space



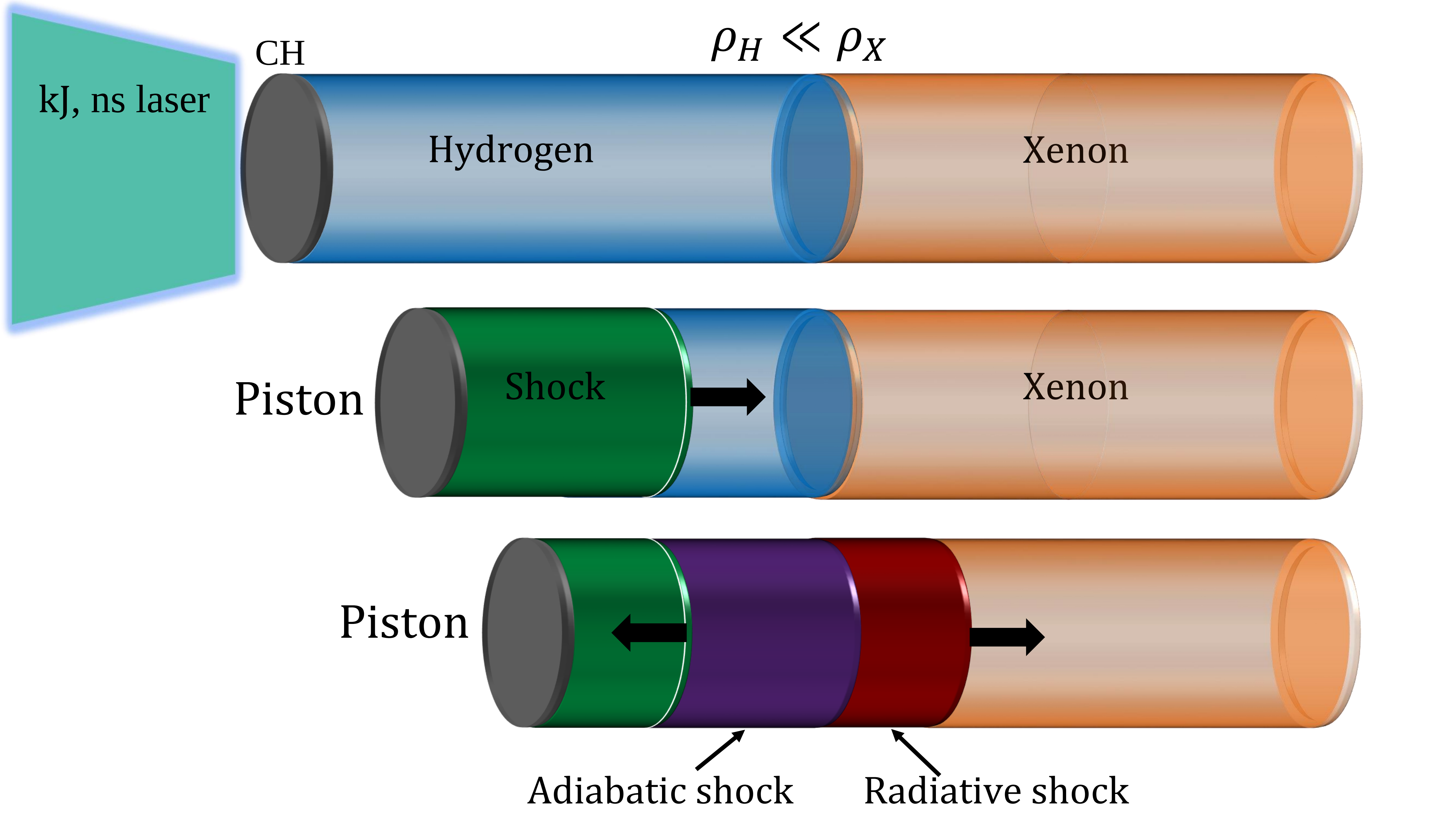
Discussion on the 1D analysis

- Self-similar analysis with an homogenous cooling
  Scalability of the study between Astro and Lab

- Estimation of the shock velocity α in function of the cooling rate λ for any β (density ratio)

- Analytical estimation of the contact discontinuity at the first time of the shocks formation
  Acceleration which could lead to some instabilities (Rayleigh-Taylor)

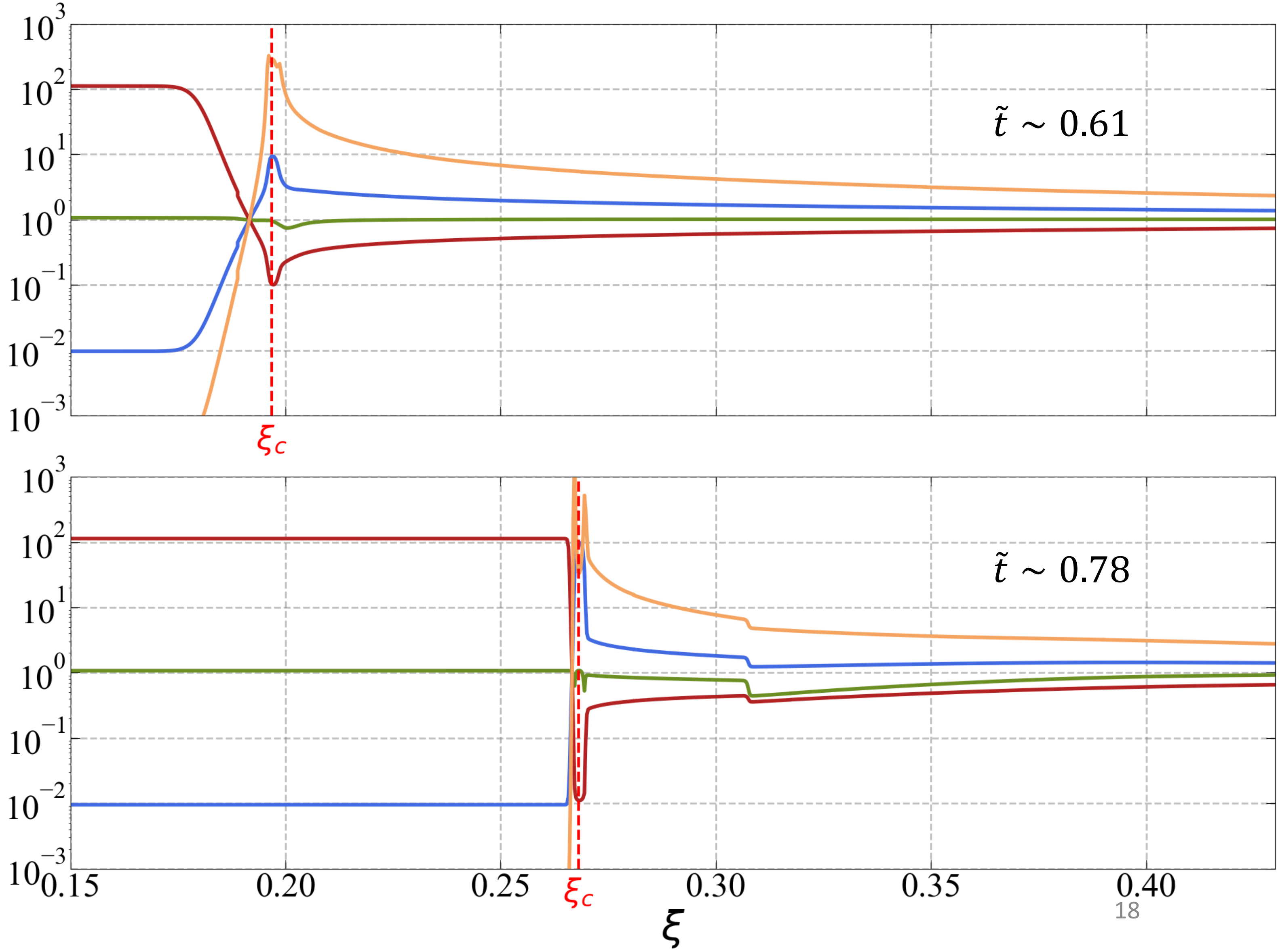
- Stability analysis / Particle mixing
- Magnetic field
- Particle acceleration
- Experiment


kJ, ns laser
CH
$\rho_H \ll \rho_X$
Hydrogen
Xenon
Piston
Shock
Xenon
Piston
Adiabatic shock
Radiative shock

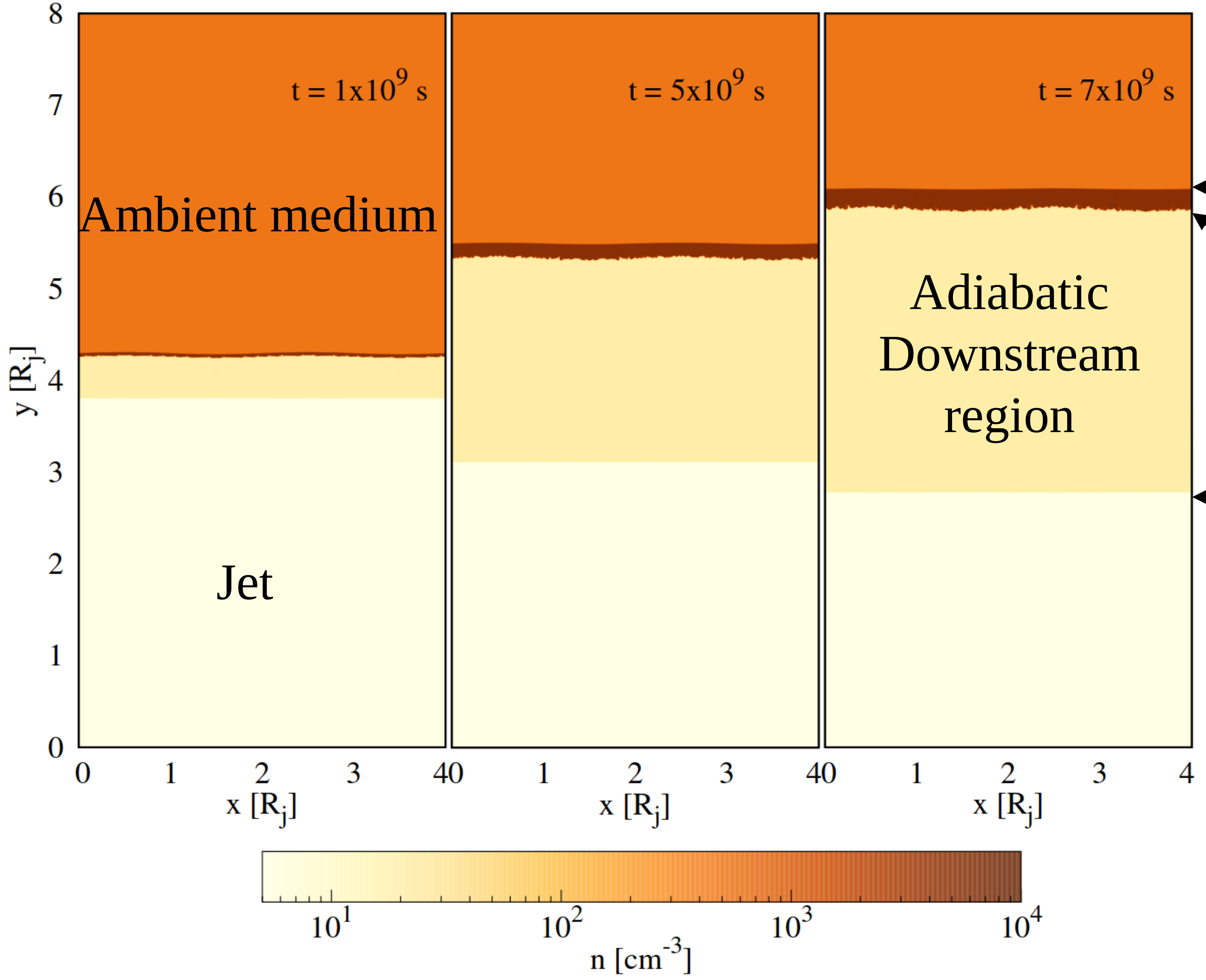

Thanks for your attention !

Thermally unstable solutions

Fundamental mode
Falle (1981)



Stability analysis



(Araudo et al. 2022)

Radiative shock front

Contact discontinuity

Adiabatic shock front

$$Q(x,y,t) = Q_0(x,t) + Q_1(x,y,t)$$

Stability analysis at self-similar time

Transverse stability

$$Q_0(x,t) = \begin{cases} \rho_0(x,t) \\ P_0(x,t) \\ v_0(x,t) \\ v_{\perp 0}(x,t) = 0 \\ \Lambda_0(x,t) \end{cases} \quad \text{and} \quad Q_1(x,y,t) = \begin{cases} \rho_1(x,y,t) \\ P_1(x,y,t) \\ v_1(x,y,t) \\ v_{\perp 1}(x,y,t) \\ \Lambda_1(x,y,t) = 0 \end{cases}$$

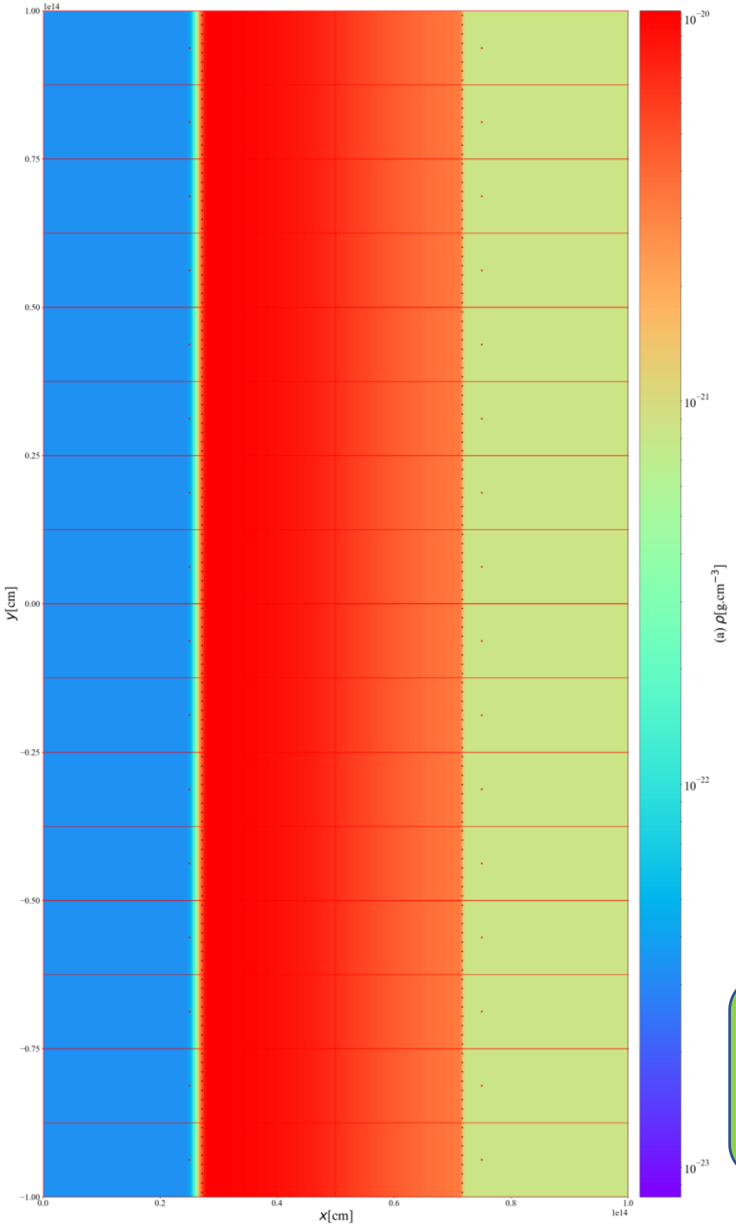
(Vishniac, 1983)
(Ryu & Vishniac, 1987)
(Vishniac, 1994)

Longitudinal stability

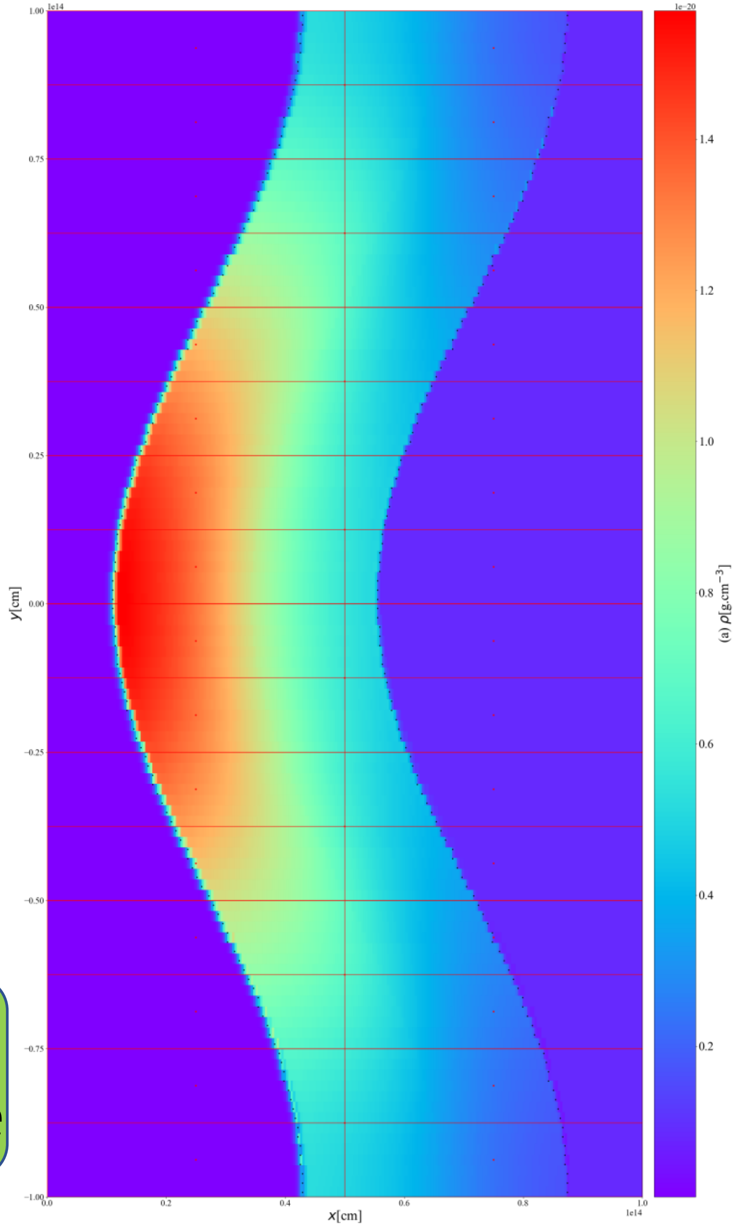
$$Q_0(x,t) = \begin{cases} \rho_0(x,t) \\ P_0(x,t) \\ v_0(x,t) \\ v_{\perp 0}(x,t) = 0 \\ \Lambda_0(x,t) \end{cases} \quad \text{and} \quad Q_1(x,t) = \begin{cases} \rho_1(x,t) \\ P_1(x,t) \\ v_1(x,t) \\ v_{\perp 1}(x,t) = 0 \\ \Lambda_1(x,t) \end{cases}$$

(Chevalier & Imamura, 1982)
(Falle, 1981)

Stability analysis

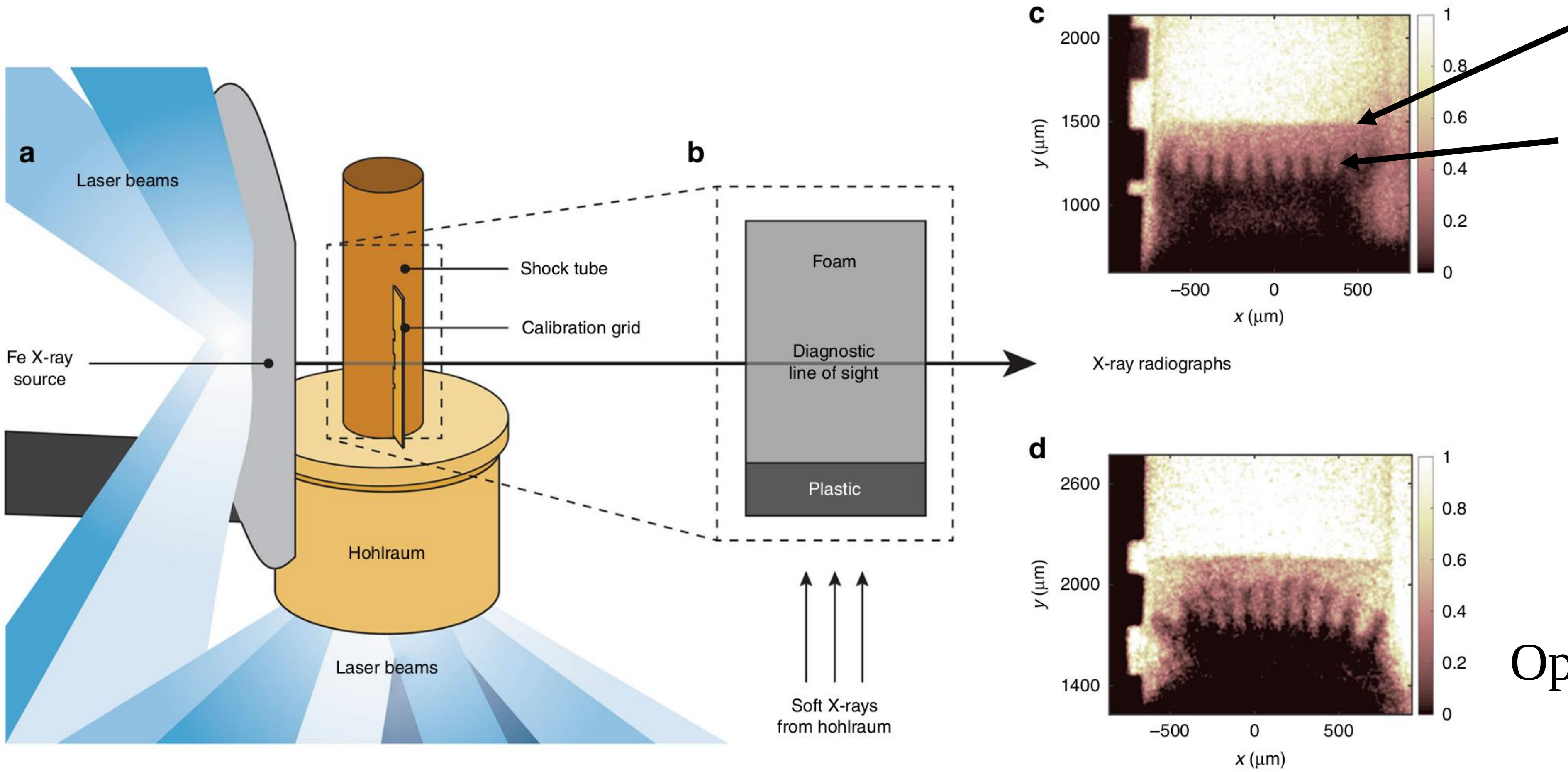


$$\begin{matrix}\rho \\ v \\ p \\ x\end{matrix} \xrightarrow{\times\, \epsilon \cos\left(\frac{yl}{x_{sh}}\right)}$$



- Growth rate estimation
- Duration of linear regime

Proposal for Laser/Plasma experiment

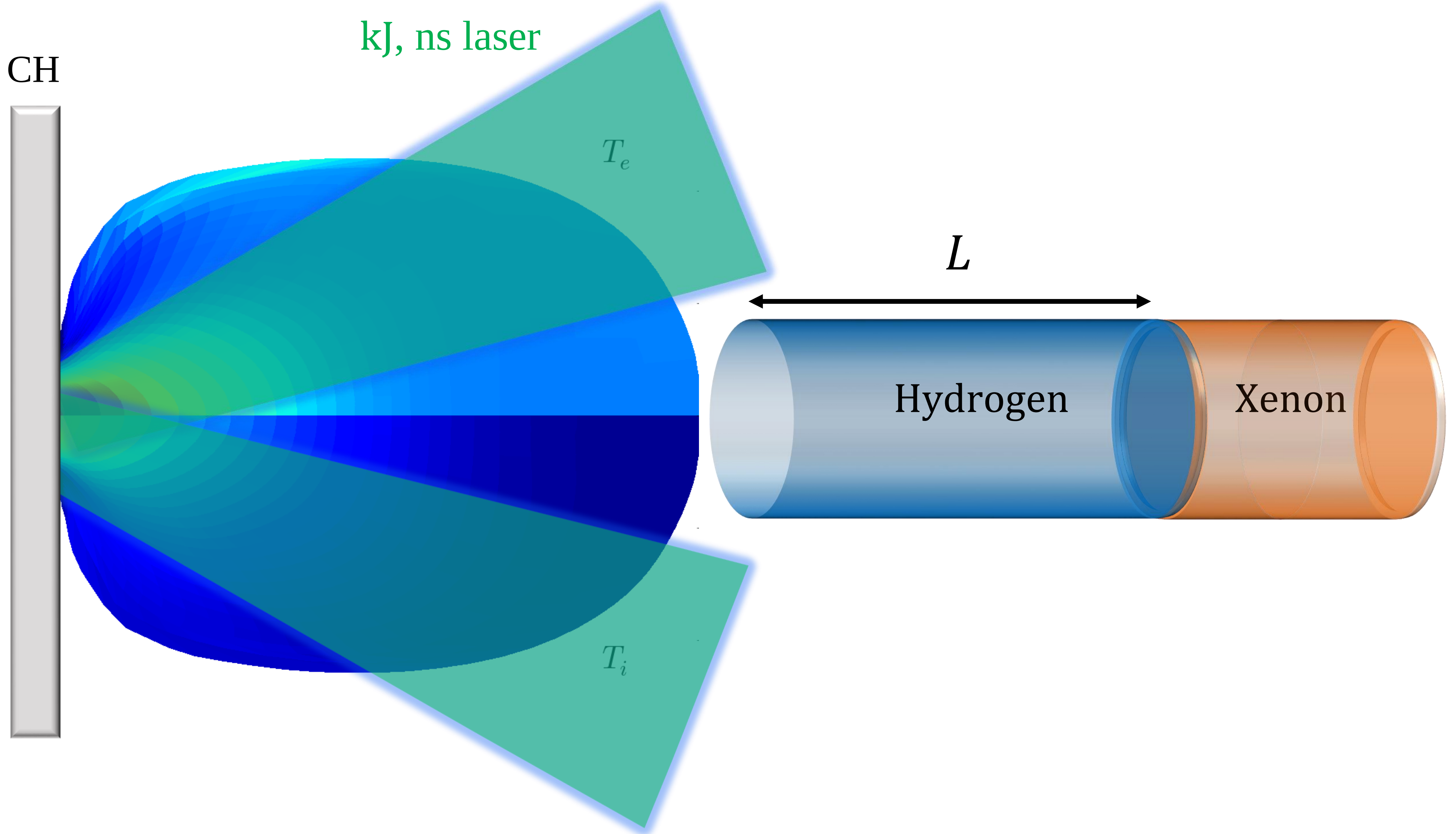


Forward shock

RT fingers

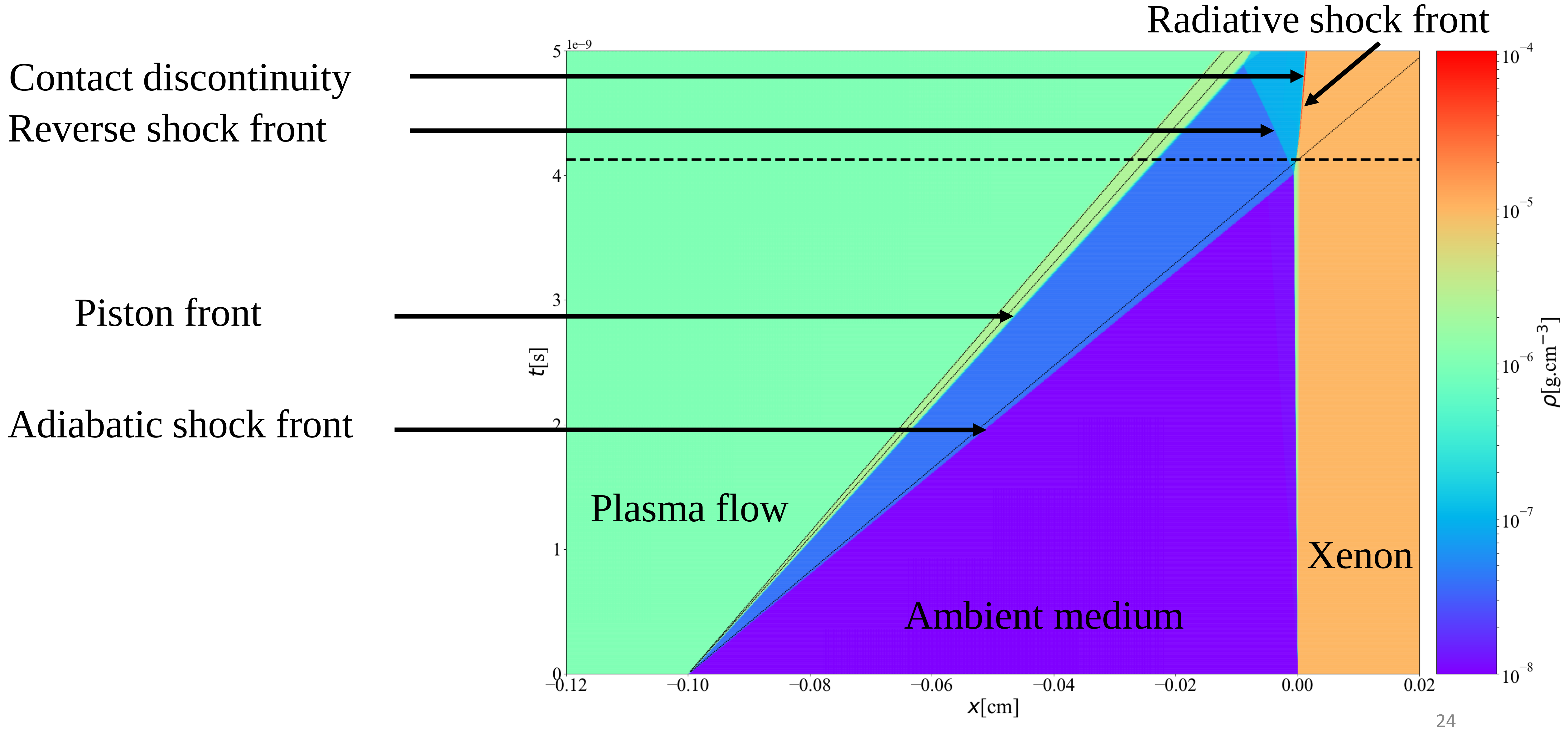
Optically thick shock
No energy loss,
No large compression

(Kuranz et al. 2018)



kJ, ns laser
CH
T_e
T_i
L
Hydrogen
Xenon

Proposal for Laser/Plasma experiment

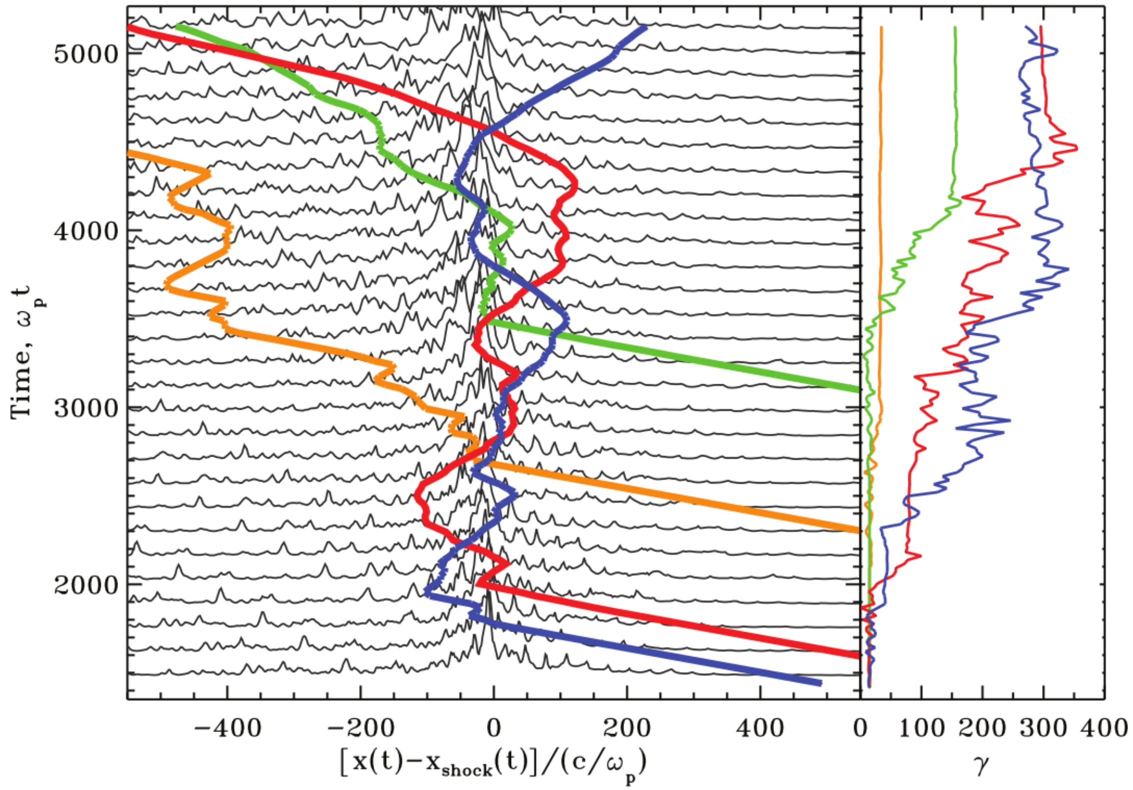


Particle acceleration

Adiabatic shocks: efficient at particle acceleration

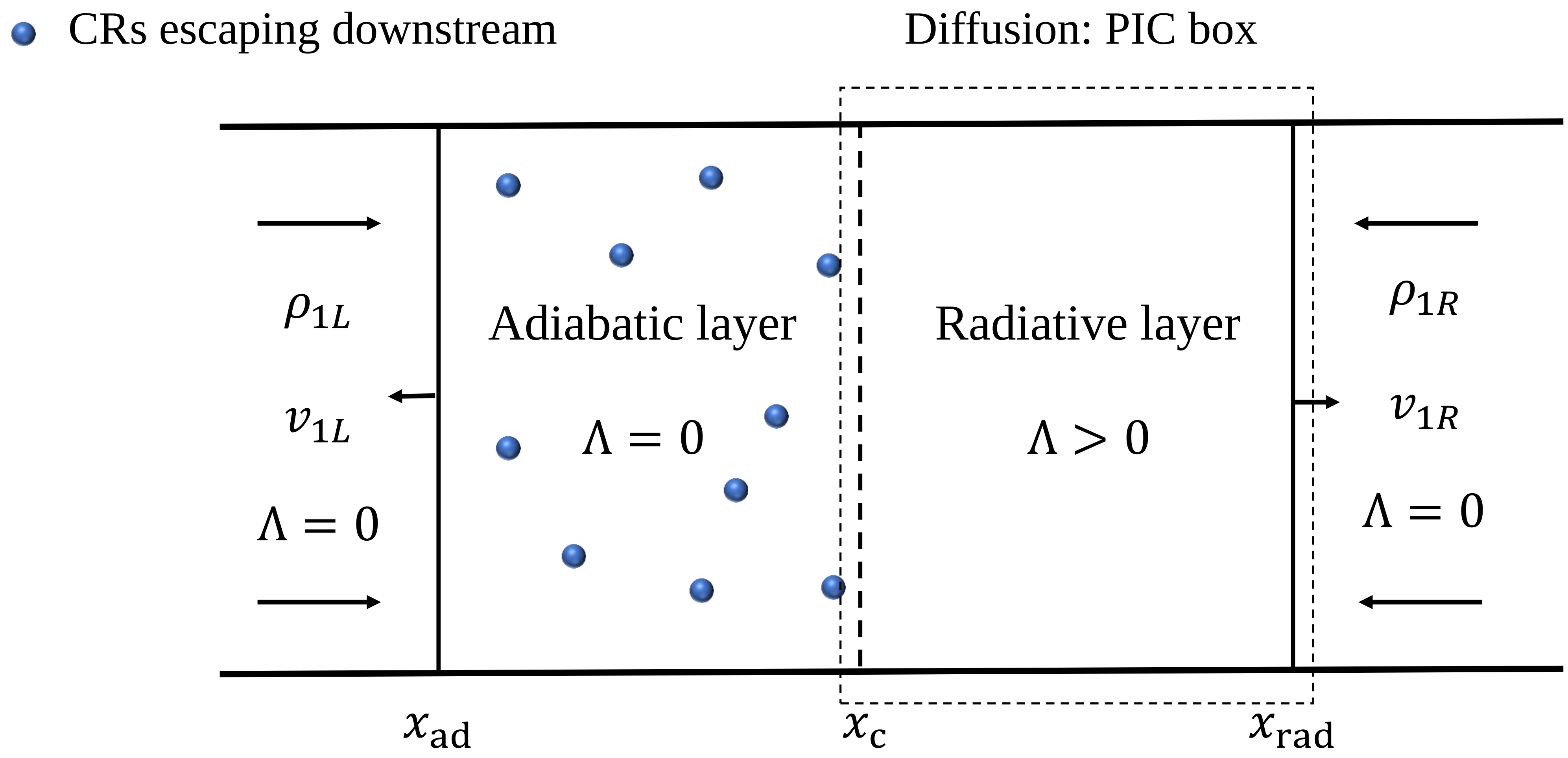
First-order Fermi acceleration

Radiative shocks: strongly compress the gas.



(Spitovsky et al. 2008)

Sketch of the particle acceleration



Numerical tools

HYBRID simulations for a complet description

- MHD code describes a thermal plasma.
- Particles are used to represent a non-thermal component (PIC module).

• A Boris pusher calculates the effect of electromagnetic fields on the particles
• The effect of charged particles on the thermal plasma can be described through the Ohm’s law (Bai et al. 2015)

Advantages over pure PIC
• No need for a large particle population
• Can take advantage of adaptive mesh refinement
• No Maxwell equations, reduces noise

Disadvantages
• Limited regime: $n_{thermal} \gg n_{non-thermal}$
• Some restrictions owing to use of ideal MHD
• Need to determine a particle injection rate

(van Marle et al., 2018)